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USE OF LONG-TERM DATA, MASS BALANCES AND STABLE ISOTOPES IN WATERSHED BIOGEOCHEMISTRY: THE HUBBARD BROOK MODEL

UTILIZACION DE DATOS DE LARGO PLAZO, BALANCES DE MASA Y ISÓTOPOS ESTABLES EN LA BIOQUIMICA DE CUENAS: EL MODELO DE HARVARD BROOK

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Currently throughout the world, human-caused environmental changes are occurring at an accelerating rate (e.g. Myers 1996; Ayrensu *et al.* 1997; Vitousek *et al*. 1997a,b; Likens 1998, 2001b; Lubchenco 1998). Such alterations (Likens 1991, 1994) include global climate change, stratospheric ozone depletion, pervasive land-use changes, toxification of the biosphere, infectious disease, invasion of alien species and loss of biodiversity, and their numerous interactions (Fig. 1). Long-term studies are especially helpful for detecting and/or evaluating: (1) the occurrence and effects of extreme events; (2) the hydrologic, biogeochemical and ecological impact of natural and anthropogenic disturbance; (3) large-scale, experimental manipulations; (4) trends in environmental variables; (5) emerging major questions or environmental problems of local, regional, national or global concern (Table I).

At the beginning of the Hubbard Brook Ecosystem Study (HBES) in 1963, several key approaches to the study of complicated and dynamic ecosystem processes were proposed, including the development of a conceptual model to guide research (Fig. 2); use of the ecosystem concept; initiation of large-scale (watershed) experimental studies with a reference ("control"); incorporation of the critical relation between biogeochemistry and hydrology; the perspective of long-term data; relating research broadly to air-land-water interactions. These approaches have been vital in guiding the research of the HBES.

Biogeochemical change has been a predominant feature of the Hubbard Brook Experimental Forest (HBEF) within the Hubbard Brook Valley of New Hampshire, USA, since the inception of the HBES in 1963. Such changes have included: decreases in SO_2 and increases in NO_x emissions (Butler *et al*. 2001; Likens *et al*. 2001); decreases in concentration and amount of SO_4^{2-}, Ca^{2+}, Mg^{2+} and increases of pH in atmospheric deposition and stream water (Likens *et al*. 1996, 1998, 2002); and cessation of forest biomass accumulation (Likens *et al*. 2002). Long-term records have been indispensable for identifying, documenting and characterizing such important changes affecting the HBEF. As a result of these long-term data, trends have become clearer and more meaningful to managers and policy makers dealing with complicated environmental issues.

Several major solutes show statistically significant, long-term decreases in both precipitation and stream water at the HBEF over the past 40 years (Fig. 3). The aquatic ecosystems of the HBEF are becoming markedly more dilute across a broad spectrum of cations and anions. For example, prior to 1970, the sum of base cation (C_B = Ca, Mg, Na, K) concentration was increasing in stream water (slope, r^2=0.98, p<0.01). Since 1970, C_B concentration has declined at a rate of 1.6 $\mu eq/L^{-1}yr^{-1}$ and acid anion concentration (AA = $SO_4^{2-} + NO_3^-$) has declined at a

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TABLE I. Some values of long-term watershed-ecosystem studies (modified from Likens 2001a).

To address scientific and environmental questions at temporal and spatial scales realistic and applicable to management

To quantify connections between ecosystems and the larger biogeochemical cycles for a region and/or the Earth. To connect inputs with outputs, such as emissions to deposition to stream output

To quantify coupling of streamflow measurements with measurements of streamwater chemistry and sediment loads to evaluate changes in water quality

To evaluate net change (accumulation or loss) of nutrients or other materials

- estimate weathering rates and gaseous flux, integrated for large areas

To provide baselines for evaluating environmental change, for example:

- global climate change (including ENSO)
- ecosystem services

To test ecological and environmental questions experimentally, for example:

- nutrient limitation
- ecosystem function (such as, nitrogen saturation; role of organic debris in streams)
- response to disturbance (natural or manipulated)
    - various agricultural practices including forestry
    - acid rain and other air pollutants
    - windstorms
    - ice storms
    - fire
    - hydrologic extremes
    - erosion
    - pesticides and other toxic substances

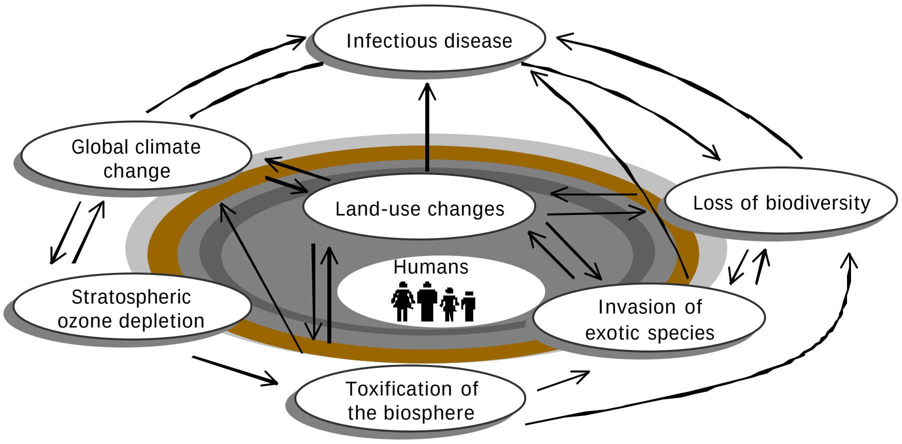

FIGURE 1. Human-accelerated environmental change (modified from Likens 2001a).

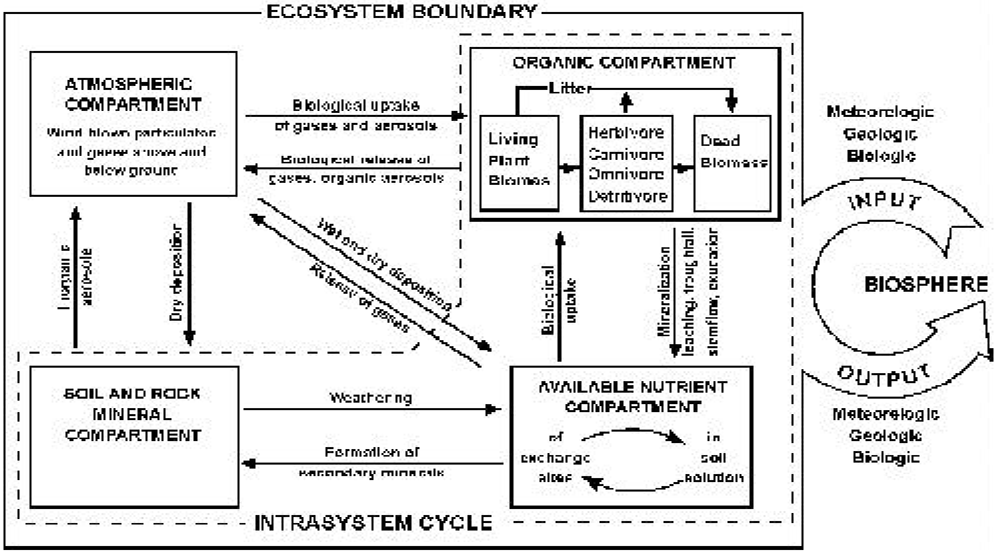

Figure 2. Model depicting biogeochemical relationships in a terrestrial ecosystem. Inputs and outputs to the ecosystem are moved by meteorologic, geologic and biologic vectors (Bormann and Likens 1967; Likens and Bormann 1972). Major sites of accumulation and major exchange pathways within the ecosystem are shown. Nutrients that have no prominent gaseous phase continually cycle within the boundaries of the ecosystem between the available nutrient, organic matter and primary and secondary mineral components tend to form an intra-system cycle. Fluxes across the boundaries of the ecosystem link individual ecosystems with the remainder of the biosphere, [from Likens and Bormann 1995].

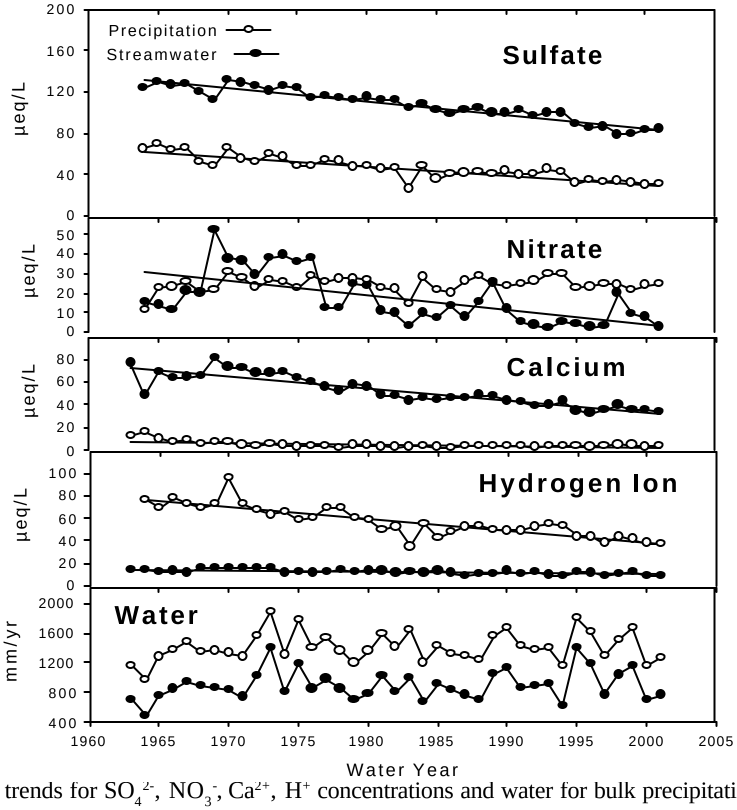

Figure 3. Long-term trends for SO_4^{2-}, NO_3^-, Ca^{2+}, H^+ concentrations and water for bulk precipitation and stream water for watershed 6 of the HBEF.

rate of 2.6 µeq/L-yr (r^2=0.94), resulting in a 50% dilution in total streamwater solute concentrations (Fig. 3).

Integrative ecosystem studies conducted at the HBEF for four decades provide an example of some insights gained by long-term studies. Short-term (3 to 5 years) studies can provide useful, but often misleading, information about long-term trends. For example, it required 18 years of continuous measurement of the chemistry of precipitation at the HBEF before it could be stated that there was a statistically significant decline in acidity of precipitation. Acidic deposition has caused a major depletion of calcium and other base cations from ecosystems of the HBEF during the past 50 years. For example, the exchangeable pools of calcium in soil were depleted by >84,500 mol/ha during this period (Likens *et al*. 1998). The accelerated loss of calcium via stream water is related strongly to changes in inputs and losses of the two dominant mobile anions, sulfate and nitrate. As a result of the depletion of calcium, ecosystems within the HBEF have become much more sensitive to continuing inputs of strong acids in atmospheric deposition (Likens *et al.* 1996). Depletion of calcium from the ecosystem has long-term implications for forest growth, as well as changes in stream ecosystems and downstream lakes within the landscape. Based upon these results, an entire-watershed manipulation of calcium additions (Wollastonite, a calcium silicate mineral) has been initiated at the HBEF to test the interactions among major biogeochemical cycles.

We have used mass balances and stable isotopes to help unravel these and other complex biogeochemical linkages (e.g. Likens *et al*. 1998, 2002; Likens and Bormann 1995; Blum *et al*. 2002; Alewell *et al*. 1999, 2000).

Having visited the watershed research site at San Pablo de Tregua (with the Millennium Group in November 2002), I have great confidence that the application of the small watershed approach (Bormann and Likens 1967) could be used there to much advantage for integrated studies in forest ecology, hydrology and biogeochemistry (see Likens 2001a).

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